AMENDMENTS TO THE SPECIFICATION

[0019] FIGS. 1-3 illustrate a preferred embodiment of the present invention. The ~~present~~ invention is a flat panel, quantum-noise-limited x-ray detector or imager 20 ("imager") for fluoroscopy. The imager 20: (i) can be provided in a "flat-screen" (*i.e.*, thin, low profile, non-bulky) format; (ii) works at speeds suitable for fluoroscopy (*e.g.*, 30 fps); (iii) converts very low levels of x-rays into electrical signals suitable for standard processing by a computer into real-time images; and (iv) operates in a quantum-limited way, down to the lowest useable fluoro x-ray dose rate, unlike existing "flat panel" detectors.

[0020] With reference to FIG. 1, the preferred imager 20 includes a cesium-iodide (CsI) screen 22, which is about 600 □m thick, for converting x-rays [[24]] (*e.g.*, 24) into photons ~~(visible light) 26.~~ (visible light), *e.g.*, 26. The screen has a high DQE (detective quantum efficiency) for x-rays, typically above 0.6. (The DQE is the measure of the combined effect of the noise and contrast performance of an x-ray imaging system, in essence a measure of information transfer, resulting in a scale of 0 to 1, with 1 indicating ~~no loss).~~ no loss.) Additionally, a very fast (*e.g.*, around f.65) demagnification lens system/array 28 is positioned behind the CsI screen 22 and comprises a number of individual lenses [[30]] (*e.g.*, 30a, 30b, 30c). The lenses [[30]] may be aspheric. The demagnification ratio of the lens system is a variable which is set within certain limits, depending on the particular geometry of the system (among other factors), to obtain quantum-limited performance, namely, performance where the limiting factor becomes x-ray quantum noise, which is attributable to the discrete and probabilistic nature of physical x-ray phenomena and their interactions.

[0021] Additionally, an array (*e.g.*, 32a, 32b, 32c) of four, nine, or sixteen CCD (charge-coupled device) image sensors [[34]] (*e.g.*, 34a, 34b, 34c) are optically coupled, via the lens system 28, to the CsI screen 22. The CCD sensors [[34]]: (i) operate at low noise levels and high signal-to-noise ratios due to on-chip gain mechanisms (and, therefore, are capable of detecting very small amounts of light); (ii) may, at option, be cooled to further reduce noise; and (iii) have an onboard CCD gain section that acts as a charge amplifier for boosting signal levels before a standard output stage. The individual photosensitive elements (*e.g.*, photodiodes) of the CCD sensors themselves (pixels) are not configured for avalanche charge multiplication, due to the additive noise issues such an approach causes, with consequential reduction in system DQE.

[0023] In the lens system, there is one lens [[30]] <u>(*e.g.*, 30a)</u> per CCD sensor [[34.]] <u>(*e.g.*, 34a).</u> Thus, a four sensor array 32c will have four lenses in the lens system 28. Additionally, length L1 (distance from lens to screen) and length L2 (distance from lens to CCD sensor) will vary from system to system, but are chosen (taking into account the particular geometry, lens types, screen, *etc.*, of the particular system) to provide quantum-limited operation. In conjunction with the pre-selected lengths L1 and L2, the lens system has an optimized demagnification ratio, such that the lens system: (i) is quantum-limited in operation with the described CCD operating mode; and (ii) can transfer very low levels of light (at least 1 to 10+ light photons per x-ray photon detected at the CsI screen) from the CsI screen 22 to each CCD pixel. In other words, the lens system is able to transfer a sample of the light it receives from the CsI screen (even down to levels of tens of light photons per x-ray photon detected at the CsI screen) to the CCD pixels such that x-ray image information is not lost. Actual levels may ideally be somewhat higher, in order to avoid statistical intensity variation, another source of additive noise. More specifically, for every x-ray scintillation in the CsI screen, the lens system will ideally collect and transfer at least a certain number (*e.g.*, in the 10's) of the light photons generated by the CsI screen (per CCD pixel, and as a function of time, per image).

[0024] In use, a standard x-ray source 40 is employed to apply low levels of x-rays [[24]] (*i.e.*, levels suitable for fluoroscopy) to a patient 42. The patient is appropriately positioned (for viewing the feature(s) of interest) in front of the CsI screen 22, with the x-ray source, patient, and CsI screen sharing a common axis. The x-rays [[24]] hit the CsI screen 22, and a portion are converted into visible light [[26.]] <u>(*e.g.*, 26)</u> As should be appreciated, because of the low levels of x-rays, there is relatively little light produced by the CsI screen (about 1000 light photons per x-ray photon scintillation). This light passes through the lens system 28 (which is specially configured for low light levels), and is demagnified onto the array 30a, 30b, or 30c of CCD sensors [[32.]] <u>(*e.g.*, 34a, 34b, 34c).</u> The sensor pixels 32 are capable of detecting these very small amounts of light, and generate electrical signals representing the sensed light. These signals or charge packets are first amplified on the CCD chip by the gain register, and are then passed to the output amplifier. Due to significant amplification in the special shift register, the signal (*i.e.*, an amplified detection signal) is now larger than the output amplifier input noise.

The output signals are then processed by a computer 44, appropriately electrically attached to the CCD sensor outputs, for correction, merging, alignment, and display on a monitor.

[0031] More specifically, while the Snoeren patent is superficially similar to the present invention, it depends on weak avalanching within the photodiode at each pixel location in an attempt to improve sensitivity and thus address this inherent noise problem. The problem with this is that each avalanche is statistically independent, so while gains of 1-10x are achieved, the gain variation both temporally and spatially causes an added noise indistinguishable from the real x-ray statistical variation (see column 4, lines 5-10 in Snoeren). In fact, this noise, described by Snoeren, is the problem the present invention addresses. According to the present invention, the CCD sensors [[34]] <u>(*e.g.*, 34, 34b, 34c)</u> do not use any avalanche photodiode multiplication at the individual pixels. Rather, an extremely small avalanche gain occurs many times (multiplicative) in a special register as a consequence of the way the CCD's are clocked. This results in a rather steady average gain factor, such that individual light photons may be discernable in the output signal. Such a mode of operation allows x-ray quantum limited fluoroscopy to the lowest usable x-ray flux levels, which is not found in the Snoeren patent due to the noisy avalanche photodiode CCD's used therein. In fact, Snoeren discusses the noise problem as a tradeoff in the patent text.

[0032] For low-light detection, the CCD sensors [[34]] <u>(*e.g.*, 34, 34b, 34c)</u> used in the present invention have a high signal-to-noise ratio (*i.e.*, they operate at low net noise levels). To minimize noise, inverted-mode operation is used to reduce dark current noise, and back illumination may be utilized as well. More significant, however, is an onboard CCD amplification mechanism, as found on the Marconi L3Vision™ sensors. Specifically, the image, store, and read-out registers of the CCD sensor are of conventional design, but there is an extended section of "gain" register between the normal serial register and the final detection node, or output amplifier. Two of the phases are clocked with normal amplitude drive pulses (typically 10 volts), whereas the drive pulses of the third phase are of a much higher amplitude (*e.g.*, 40-50 V). Before each third phase electrode is another electrode held at a low d.c. voltage (*e.g.*, 2 V). The large potential difference between the low voltage electrodes and the high voltage electrodes gives rise to a high electric field in the underlying silicon such that electrons transferred to the third phase electrodes during the normal clocking sequence can experience

slight and well-controlled avalanche multiplication, which thereby increases the number of electrons in the charge pocket, *i.e.*, produces gain. Although the mean gain per stage is small, typically about 0.01 (to help avoid avalanche variation), over the large number of stages of a typical read-out register the total gain can be quite high, and also settable by the user. This strong signal is passed on to a conventional CCD output amplifier. However, the noise of the amplifier is now divided by the gain factor of the multiplication register, which will reduce the effective output read noise per light photon, so the signal-to-noise ratio is improved.

[0035] The preferred lens system 28 will now be discussed in further detail.

[0041] The next step is to calculate the ~~collection efficiency~~ "collection efficiency" ("CE") of the lens system, which is deemed to be that fraction of light photons emitted by the CsI screen that actually enters the lens system. Assuming a Lambertian or semi-Lambertian distribution (see above), and a given lens f-number F_{num}, the collection efficiency is given by:

$$CE = [\, 1 + 4 \cdot F_{num}{}^2 \cdot (1 + (1 / m))^2 \,]^{-1}$$

This equation was derived by expressing the lens collection efficiency for a Lambertian distribution (CE = $\sin^2$□) in terms of magnification m and lens f-number F_{num}, where □ is the polar angle subtended by the lens as measured from the axial point on the CsI screen (point on the cylindrical axis of the lens). It should be noted that an f-number of $F_{num} = 0$, which indicates a theoretical infinite aperture, would result in a CE = 1 (*i.e.*, intuitively, since the aperture is infinite, all light is drawn into the lens, resulting in a perfect collection efficiency).